PROCEEDINGS OF SCIENCE

MINERvA: Results and Prospects

Deborah A. Harris[a,b,*]

On behalf of the MINERvA Collaboration

[a] *York University,*
Department of Physics and Astronomy, Toronto, Ontario, M3J 1P3 Canada

[b] *Fermi National Accelerator Laboratory, Batavia, Illinois, 60510, USA*

E-mail: deborahh@yorku.ca

MINERvA is a dedicated neutrino cross section experiment that ran in the NuMI beamline at Fermilab from 2009 through 2019. MINERvA has made a broad suite of measurements that are informing the neutrino interaction models in use by not only today's oscillation experiments but also by future generations of oscillation experiments. Of particular interest are MINERvA's measurements of the quasielastic-like and pion production processes, since those channels dominate the oscillation landscape. MINERvA has also ushered in the era of using neutrino electron scattering to make precise flux predictions, another important input for oscillation experiments. This paper briefly describes a few recently published results from MINERvA's neutrino and antineutrino scattering sample on the hydrocarbon target including its new flux constraints, and points to some upcoming quasielastic and pion production results that will showcase simultaneous measurements of exclusive final states across different nuclei, ranging from carbon and water to iron and lead.

Neutrino Oscillation Workshop-NOW2022
4-11 September, 2022
Rosa Marina (Ostuni, Italy)

*Speaker

https://pos.sissa.it/

PoS(NOW2022)032

1. Introduction

As neutrino oscillation experiments collect more statistics, the importance of correct neutrino interaction modeling becomes more pronounced. Although most models are based on neutrino-nucleon scattering, the field is developing more sophisticated treatments of the nuclear environment and its effect on the simple neutrino-nucleon picture. In particular, that environment can modify both the initial state of the scattered nucleons (for example through multinucleon correlations) and the final state particle energies that eventually are detected. In addition, we as a field are becoming more aware of the limitations of our measurements, regardless of what detector technology we are using. For example, there is a well-developed understanding of the dangers of reconstructing neutrino energies using only the outgoing lepton angle and momentum, as is done for Cerenkov-based detector. The field is starting to better appreciate the shortcomings that calorimetric detectors have in measuring energy, since neutrons will always be challenging to measure even in the most fine-grained calorimetric detector. The MINERvA experiment has been leveraging its large data set and precise flux prediction to benchmark a number of commonly-used neutrino interaction models, and we frequently see discrepancies with the predictions of those models. The most striking discrepancies are coming from comparisons of cross section ratios between lead and iron compared to hydrocarbon. This article describes some of MINERvA's newest results on cross sections across several nuclei, as well as a few new results on plastic scintillator.

2. Detector and Beamline

The MINERvA detector is based primarily on a segmented scintillator inner tracking region, with electromagnetic and hadronic calorimetry surrounding that inner tracker[1]. The upstream portion of the detector contains five planes of passive solid material comprised of iron, lead, and graphite, plus a liquid water target, all of which are surrounded by the segmented scintillator planes. The MINERvA detector sits upstream of the MINOS near detector [2] which can identify the momentum and charge of the muons that originate in MINERvA and are tracked in MINOS. The hadronic energy scale of the MINERvA detector has been determined by test beam measurements on a small-scale prototype [3].

The MINERvA detector sits in the NuMI beamline [4] at Fermi National Accelerator Laboratory, and the results reported here all come from the "Medium Energy" configuration of the beamline, which is a broad-band beam with a peak neutrino energy of about 5 GeV. The flux prediction is constrained by hadron production measurements [5] as well as in-situ measurements of neutrino-electron scattering [6], antineutrino-electron scattering [7], and inverse muon decay [8]. The flux prediction is also informed by comparing the energy distribution of low-recoil events as a function of total neutrino energy, since misalignments in this beamline have very distinct signatures [9]. In MINERvA's recently completed its analysis of antineutrino-electron scattering in its antineutrino-enhanced beam [7], the experiment leverages the correlations between its neutrino and antineutrino flux predictions and uses neutrino-electron scattering in both modes to reduce the flux uncertainties in both modes. The resulting integrated flux uncertainty when all three measurements are combined as constraints is 3.3% (4.7%) for the neutrino-enhanced (antineutrino-enhanced) beam.

3. Results on Hydrocarbon

3.1 Low Recoil Cross-Section Results

Multinucleon correlations were first seen in electron scattering measurements by measuring the cross section as a function of transferred energy, and seeing extra strength in the cross section between the quasielastic peak and resonance production [10]. This was later confirmed by the measurements of proton-neutron final states in neutral current scattering. In neutrino scattering events the initial neutrino energy is not known, and final state neutrons can also take away part of the neutrino energy. MINERvA was able to isolate multinucleon correlations in its low energy data set by measuring "available energy" as a function of 3-momentum transfer for low-recoil events, where the 3-momentum transfer is primarily determined by the muon kinematics with only a small component coming from the hadronic system ([11] and [12] for neutrino- and antineutrino-mode results, respectively). The available energy is that energy that is available to create a signal in the scintillator: kinetic energies of charged pions and protons and total energies of neutral pions and photons. MINERvA has extended that analysis in the medium energy beam [13], where the higher statistics and higher beam energy has meant the possibility of reaching out to higher recoil events. The presence of multi-nucleon effects is still evident at comparable levels compared to the low energy measurements, but now there are significantly more models that attempt to simulate this process. No model successfully predicts this behavior at all momentum transfers measured, but this new measurement will help future model development.

3.2 Quasielastic-like Cross-Section Results

Quasielastic-like neutrino interactions on a scintillator detector offer a unique opportunity to separate out different nuclear effects. Given the high correlation between the sum of final state proton kinetic energies and visible energy in a scintillator detector, that visible energy becomes a reasonable proxy for the energy transferred to the nucleus in quasielastic-like neutrino interactions. This energy transfer can also be estimated from the muon momentum and angle given a known incoming neutrino direction. MINERvA has collected well over a million charged current quasielastic-like neutrino interactions, and has produced three-dimensional cross sections, where the three dimensions are the muon transverse and longitudinal momenta and the sum of the proton kinetic energies [14]. Pion absorption in the parent nucleus, or multinucleon scattering processes are more likely to arise in regions where the transverse muon momentum is low but the total proton kinetic energy is high. Conversely, if a high energy proton is created in a quasielastic interaction but is then absorbed in the nucleus and emitted in the form of neutrons, that process shows up at high transverse muon momentum and low total proton kinetic energy. Both of these processes are much more common in MINERvA's simulation than in the data, where the simulation was tuned on MINERvA's low energy results and external measurements from deuterium scattering. Another way to examine these events is to directly compare the amount of energy that a quasielastic-like hypothesis would suggest should be added to the muon energy to get the total neutrino energy in the event and the sum of proton kinetic energies for these events. By doing this, MINERvA compares the neutrino energy reconstruction from a Cerenkov-style detector to that of a fully active detector, for example one made of scintillator or a liquid argon time projection chamber (TPC), for the same input neutrino energy distribution. As can be seen in [14], the two strategies would not yield the same neutrino energy

PoS(NOW2022)032

distribution in data as in simulation, a trend that persists along several values of muon longitudinal momentum.

4. Results on iron, lead, water

The high statistics collected in the medium energy beam allows direct A-dependence measurements for exclusive processes. Several analyses on the nuclear targets were presented in this talk, which represent a first chance to directly measure the effect of changing the parent nucleus in the interaction while keeping the detector and flux the same. Given that the target masses of the lead and iron targets in MINERvA are about one ton, and the scintillator is about 8.3 tons, and the flux times the integrated protons on target is at least two times four times larger in the medium energy data set compared to the low energy data set, the statistics that MINERvA has on its nuclear targets in the medium energy neutrino beam is at the same level as those on its plastic target in the low energy neutrino data set.

4.1 Coherent Pion Production

Coherent pion production is a poorly understood process whose neutral current channel is a small but non-negligible background for oscillation analyses. In this process the neutrino scatters coherently off the entire nucleus, leaving it intact and transferring almost no energy but producing a neutral or charged pion in the final state. The cross section scaling as a function of atomic number has been predicted to be either $A^{1/3}$ or $A^{2/3}$, depending on the model. MINERvA's low energy measurement of the charged current channel [15] showed that the various models on the market at the time were not correctly predicting the pion energy spectra. Those models have since been improved to agree better with the MINERvA low energy results, and are currently in use by the community. MINERvA has measured the A-dependence of coherent charged current pion production [16] and has demonstrated that although the pion energy spectrum for carbon (now) matches the models on the market reasonably well, neither the spectrum on iron or lead is well modeled, where the discrepancy with the model grows with atomic number. For neutrino energies above 10 GeV, the A-scaling is consistent with $A^{2/3}$ for both iron and lead, for lower neutrino energies the A-scaling is significantly below $A^{2/3}$, where for iron it is consistent with $A^{1/3}$ scaling.

4.2 Quasielastic-like Scattering

MINERvA has collected 100k event-sized samples of quasielastic events on its nuclear targets, and has two new measurements which are being prepared for publication and were presented at this NOW2022. The muon kinematics for these events are still well-measured, provided the muon angle with respect to the neutrino beam direction is less than or equal to 17°. Although the sum of the proton kinetic energies cannot be as accurately measured as on scintillator because of the passive material in the nuclear target region, proton tracking is still possible and so for events with high enough momentum protons, MINERvA is able to reconstruct transverse kinematic imbalance variables in its nuclear targets, similar in statistics to those reported from the Low Energy Beam [17, 18]. MINERvA has measured the quasielastic-like cross section on Carbon, water, iron and lead, and compared it to the cross section on its scintillator detector. While the cross section per nucleon ratio between Carbon and CH, and water to CH are consistent with unity, MINERvA is seeing a larger ratio for iron and lead to CH than the current models predict. This may be due in part to mis-modeling of pion absorption: MINERvA has also measured pion production in its nuclear targets [19], and sees a relative suppression of the ratio of pion production cross sections for iron or lead divided by scintillator compared to the simulation. If fewer pions are produced than predicted by the simulation, then there are two possibilities for how this might manifest in the quasielastic-like sample. If the pions predicted by the simulation are then absorbed in the nucleus due to final state interactions, then those events would show up as quasielastic-like events in this analysis, and would be an excess in quasielastic-like production compared to the simulation. If initial pion production was the reason for this suppression, then the quasielastic-like contribution would also show a deficit. The quasielastic-like results presented at this meeting suggest that the deficit seen in the pion production analyses is due to final state interactions, since there is a surplus of events over prediction in the quasielastic-like channel.

5. Conclusion

MINERvA continues to produce novel measurements of neutrino and antineutrino interaction cross sections, thanks to its high statistics data sets and its high-granularity detector combined with low flux uncertainties and its multiple nuclear targets. These measurements will help inform future models of exclusive neutrino interactions on nuclei and the role that the nuclear environment plays in each of these interactions. MINERvA is also preparing a data preservation product so that the particle physics community can analyze these data for many years to come, while we as a community build the next generation of neutrino oscillation experiments.

References

[1] L. Aliaga *et al.* (MINERvA Collaboration), Nucl. Instrum. Meth. A **743**, 130 (2014) [arXiv:1305.5199 [physics.ins-det]].

[2] D. G. Michael *et al.* (MINOS Collaboration), Nucl. Instrum. Meth. A **596**, 190 (2008) [arXiv:0805.3170 [physics.ins-det]].

[3] L. Aliaga *et al.* [MINERvA], Nucl. Instrum. Meth. A **789**, 28-42 (2015) doi:10.1016/j.nima.2015.04.003 [arXiv:1501.06431 [physics.ins-det]].

[4] P. Adamson *et al.*, Nucl. Instrum. Meth. A **806**, 279 (2016) [arXiv:1507.06690 [physics.acc-ph]].

[5] L. Aliaga *et al.* [MINERvA], Phys. Rev. D **94**, no.9, 092005 (2016) doi:10.1103/PhysRevD.94.092005 [arXiv:1607.00704 [hep-ex]].

[6] E. Valencia *et al.* [MINERvA], Phys. Rev. D **100**, no.9, 092001 (2019) doi:10.1103/PhysRevD.100.092001 [arXiv:1906.00111 [hep-ex]].

[7] L. Zazueta *et al.* [MINERvA], [arXiv:2209.05540 [hep-ex]].

[8] D. Ruterbories *et al.* [MINERvA], Phys. Rev. D **104**, no.9, 092010 (2021) doi:10.1103/PhysRevD.104.092010 [arXiv:2107.01059 [hep-ex]].

[9] A. Bashyal *et al.* [MINERvA], JINST **16**, P08068 (2021) doi:10.1088/1748-0221/16/08/P08068 [arXiv:2104.05769 [hep-ex]].

[10] A. Schmidt *et al.* [CLAS], Nature **578**, no.7796, 540-544 (2020) doi:10.1038/s41586-020-2021-6 [arXiv:2004.11221 [nucl-ex]].

[11] P. A. Rodrigues *et al.* [MINERvA], Phys. Rev. Lett. **116**, 071802 (2016) doi:10.1103/PhysRevLett.116.071802 [arXiv:1511.05944 [hep-ex]].

[12] R. Gran *et al.* [MINERvA], Phys. Rev. Lett. **120**, no.22, 221805 (2018) doi:10.1103/PhysRevLett.120.221805 [arXiv:1803.09377 [hep-ex]].

[13] M. V. Ascencio *et al.* [MINERvA], Phys. Rev. D **106**, no.3, 032001 (2022) doi:10.1103/PhysRevD.106.032001 [arXiv:2110.13372 [hep-ex]].

[14] D. Ruterbories *et al.* [MINERvA], Phys. Rev. Lett. **129**, no.2, 021803 (2022) doi:10.1103/PhysRevLett.129.021803 [arXiv:2203.08022 [hep-ex]].

[15] A. Mislivec *et al.* [MINERvA], Phys. Rev. D **97**, no.3, 032014 (2018) doi:10.1103/PhysRevD.97.032014 [arXiv:1711.01178 [hep-ex]].

[16] M. A. Ramírez *et al.* [MINERvA], [arXiv:2210.01285 [hep-ex]].

[17] T. Cai *et al.* [MINERvA], Phys. Rev. D **101**, no.9, 092001 (2020) doi:10.1103/PhysRevD.101.092001 [arXiv:1910.08658 [hep-ex]].

[18] X. G. Lu *et al.* [MINERvA], Phys. Rev. Lett. **121**, no.2, 022504 (2018) doi:10.1103/PhysRevLett.121.022504 [arXiv:1805.05486 [hep-ex]].

[19] A. Bercellie *et al.* [MINERvA], [arXiv:2209.07852 [hep-ex]].

PoS(NOW2022)032